CAAP Quarterly Report

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Contract Number: *DTPH5614HCAP04*

Prepared for: *Dr. James Merritt, PHMSA-DOT*

Project Title: *Optimized Diagnosis and Prognosis for Impingement Failure of PA and PE Piping Materials*

Prepared by: *University of Colorado-Denver, Arizona State University*

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Business and Activity Section

(a) Generated Commitments

Pipeline infrastructure and its safety is critical for the recovering of U.S. economy and our standard of living. Statistics from U.S. Department of Transportation (DOT) and Gas Technology Institute (GTI) show the decline in use of steel and cast iron piping materials is significant in recent years and the increase in pipeline system size is largely due to plastic pipe installations. However, failure inevitably occurs in plastic piping materials and impingement failure is caused by high localized stress concentration combined with defects and inclusions. Previous research efforts were mainly focusing on PE materials, efficient and effective impingement damage diagnosis and prognosis of various types of new plastic piping materials still remain unaddressed and challenging. The proposed research will fundamentally understand and characterize the failure modes and associated material behaviors for modern plastic piping materials. The proposed optimized diagnosis and prognosis approaches will thoroughly investigate and compare the dominating PE materials (make up nearly 97% of current plastic pipes) and the emerging PA pipes that can operate at much higher pressures and be installed using existing PE tools and techniques. If successful, this study can help to effectively maintain and improve the reliability of pipeline systems, and ultimately reduce the environmental consequences because of a pipeline catastrophic failure.

The overall objectives of the proposed research are two-fold: optimized diagnosis-find existing impingement damage at the earliest stage before it becomes failure critical in PE and PA materials, conduct comprehensive comparison studies to identify the differences in micro-cracking mechanism between these two materials; and optimized prognosis - accurately predict the remaining strength and RUL of PE and PA components through mechanical modeling and experimental investigations.

The eighteen-month effort will establish a framework composed of both physical (CU) and mechanical modeling (ASU) with optimized parametric studies both numerically and experimentally, and models validation during the first project year (month 1 to month 12). A thorough anomaly detection, characterization and sensitivity analysis for both optimized diagnosis and prognosis algorithms will be carried out in the second project year (month 13 to month 16). Building upon achieving these research milestones, a model-assisted detection and prediction framework with the integrated diagnosis and prognosis capabilities will be realized and tested in field at the last phase of this project (month 16 to month 18). The specific technical objectives are addressed through the following two major research tasks, each has three subtasks:

Task 1 focuses on the sensing physics modeling of impingement failure diagnosis and experimental investigation assisted by model-based inversion techniques. Three subtasks are proposed:

(1.1) element-free Galerkin’s method (EFG) development for the electromagnetic modeling of arbitrary and micro-scale crack initiation and propagation due to impingement; (1.2) model-based inversion for ultra-fast impingement failure reconstruction and sensing assisted by compressed sensing techniques; (1.3) demonstration of optimized diagnosis capabilities using electromagnetic diffraction tomography array.

Task 2 focuses on the mechanical modeling of impingement failure and experimental investigation. Three subtasks are proposed: (2.1) extended finite element method (XFEM) and cohesive zone modeling (CZM) for the crack initiation and propagation simulation; (2.2) experimental investigation of impingement effect on the failure of investigated materials; (2.3) parametric study and sensitivity analysis for the optimized prognosis algorithms.

(b) Status Update of Past Quarter Activities

Kick-off meeting:

Program director, Dr. James Merritt visited Arizona State University and a project kick-off meeting was held on October 30, 2014. The PIs, Dr. Yiming Deng (CU-Denver) and Dr. Yongming Liu (ASU) reported the planned activities for next year and anticipated project milestones, and discussed specific research and education objectives of this funded project with Dr. Merritt. All PhD, MS and undergraduate students in the PARA LAB at ASU and LEAP Group at CU-Denver attended the meeting. Gas Technology Institutes (GTI) and Arkema Inc. participated the meeting as industry collaborators as well. Detailed discussion on the current R&D map for this project was conducted and specific research objectives were identified. The challenges of understanding the combining mechanism due to the proposed impingement damage, lift-off variation of the new sensing techniques due to thickness of coating materials and different regulations of different piping materials were also discussed. GTI agreed to provide technical assistance and guide through this newly launched project and Arkema will provided testing samples in early 2015. The project overview is illustrated in Figure 1. The CAAP students sponsored by this program were identified and encouraged by the program director to work closely with university research labs, industries and USDOT to get more training and be better prepared for their career in pipeline safety. Both presentations slides of CU and ASU have been uploaded to the R&D database.

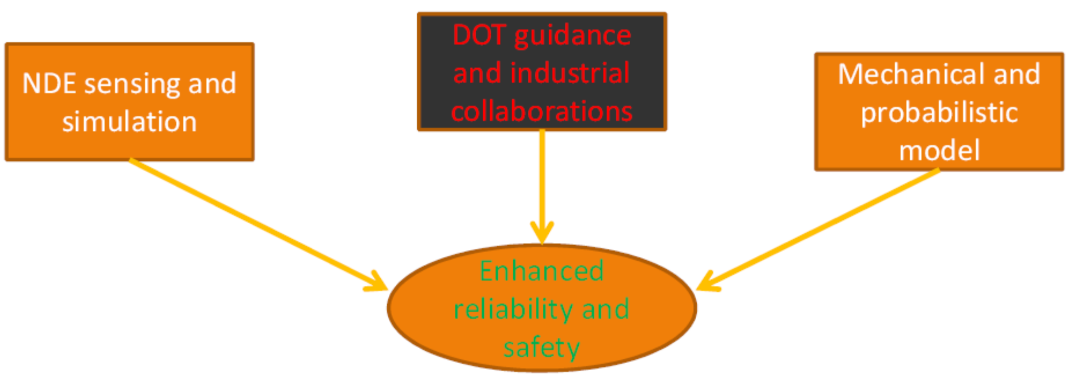

Fig. 1. Project Overview Schematic

Task 1- Sensing physics modeling of impingement failure diagnosis and experimental investigation assisted by model-based inversion techniques

In Quarter 1, the PIs and CAAP research teams at the CU-Denver and ASU started Task 1, the modeling task and had satisfactory progress in getting preliminary results. After the kick-off meeting discussion, PA-11 and PA-12 materials with impingement type damage will be emphasized for this funded research. The critical component of the proposed sensing system, near-field microwave simulation and its interaction with plastic materials will be modeled in the next two quarters using proposed numerical methods. Both CU and ASU teams have started to develop physical and mechanical modeling tools to better assist the multi-resolution sensing system development. The preliminary impingement damage reconstruction results were shown in Figure 2. However, conventional model-based defects reconstruction is very time-consuming and computationally expensive. An innovative impingement defective pipe geometry reconstruction algorithm is being investigated to address this challenge by strategically reducing the number of measurements assisted by the concept of compressed sensing. CS-based imaging speed improvement experimentally is also been studied and discussed in the next section: problems/challenges as well.

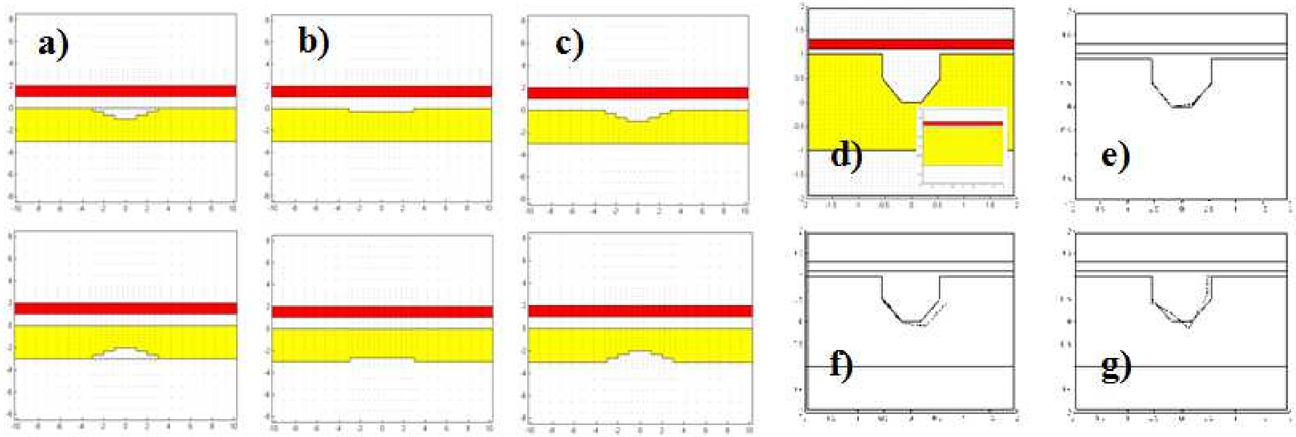

Fig. 2. Impingement OD and ID defects reconstruction using state-space search method (Left): (a) true profile, (b) initial guess and (c) reconstructed profile and deeper OD defects reconstruction; using gradient search method (Right): (d) true profile and initial guess and reconstructed profiles with (e) 5% measurement noise, (f) 15% measurement noise and (g) 25% measurement noise

A 3D simulation study was simultaneously conducted using FEKO software in Q1 and the simulation geometry is shown in Figure 3 for an antenna array sensor. Preliminary physical modeling result is shown in Figure 4. Further investigation will continue in the next quarter.

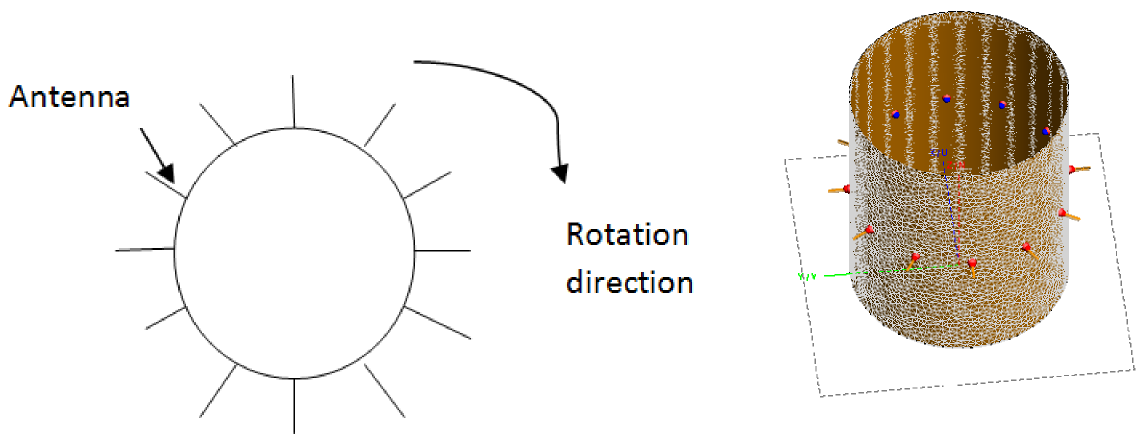

Fig. 3. 3D simulation for the NFMW imaging system with array geometry

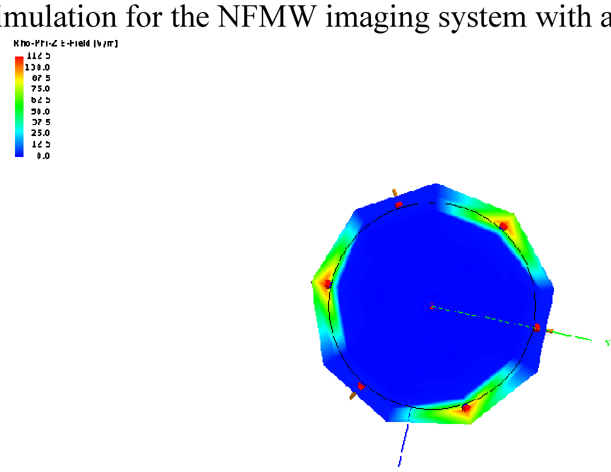

Fig. 4. Three channel NFMW imaging sensors with radiation pattern for pipe sections without impingment damage.

Task 2-Mechanical modeling on impingement failure

Task 2 focuses on the mechanical modeling and comparison of PA and PE materials. Preliminary analysis with simplified constitutive modeling is performed during the current reporting period. Details are shown below.

Modeling and simulation were carried out in Abaqus software as it gave the freedom of using XFEM and CZM technique. Both PA-11 material and HDPE (Poly – Ethylene) material are simulated. Simplified constitutive model from literature is used. The focus is on the methodology demonstration and the parametric study for the cavity radius effect on the final failure for the two materials. The following material model was used to carry out the simulations.

- Mod. of Elasticity – 961 MPa
- Poisson's Ratio – 0.38
- Tensile Strength, Utimate – 23.4 MPa
- Tensile Strength, Yield – 32.4 MPa
- Tangent Mod. – 2.5% of Mod. of Elasticity
- CZM, Criterion – Max. Principal Stress
- CZM, Value – 30 MPa
- CZM, Damage Evolution – Energy, Exponential Softening
- CZM, Fracture Energy – 620 KJ/m2

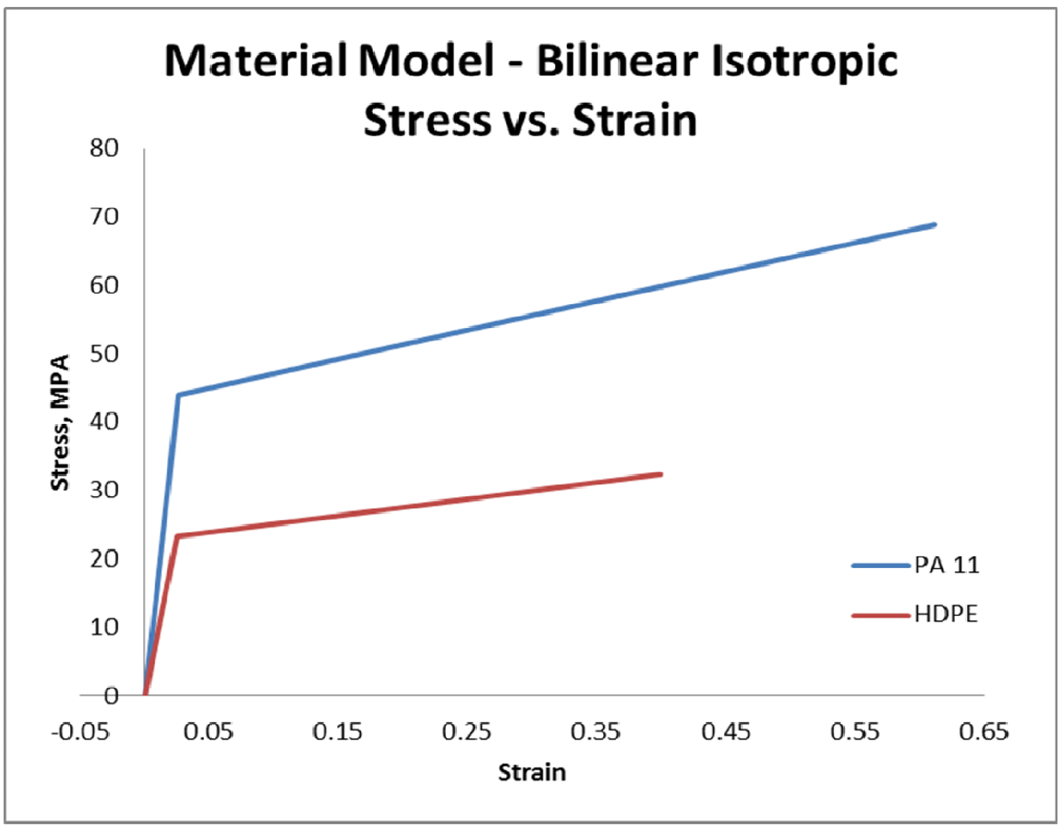

Fig. 5 Comparison of material models between PA-11 and HDPE

A screenshot for the crack propagation behavior is shown in Fig. 6. The qualitative behavior is similar for both materials with different quantitative failure strength.

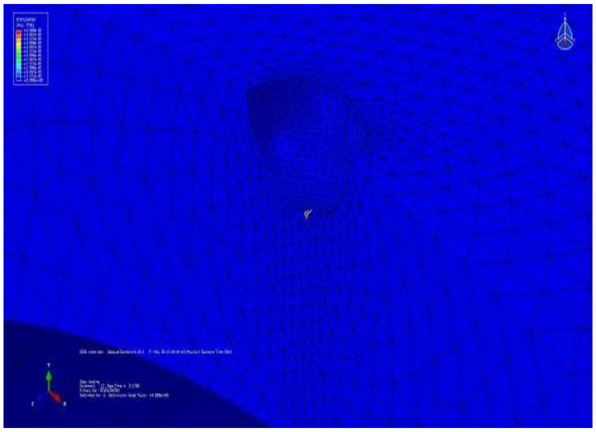
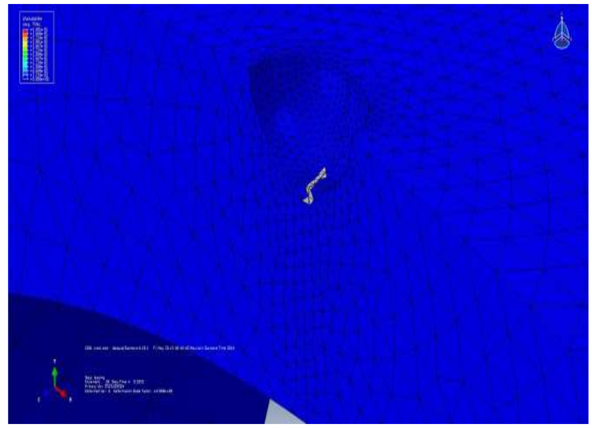
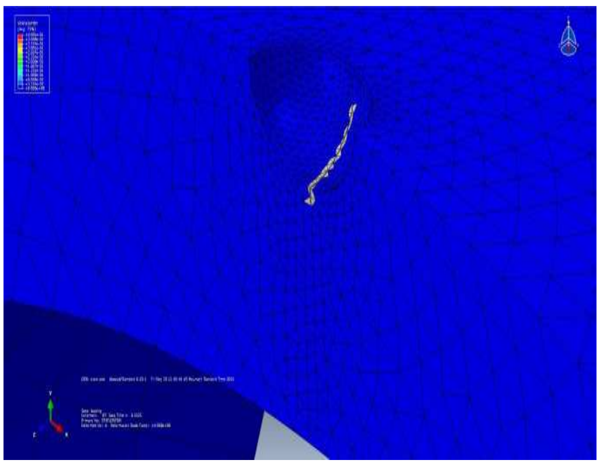
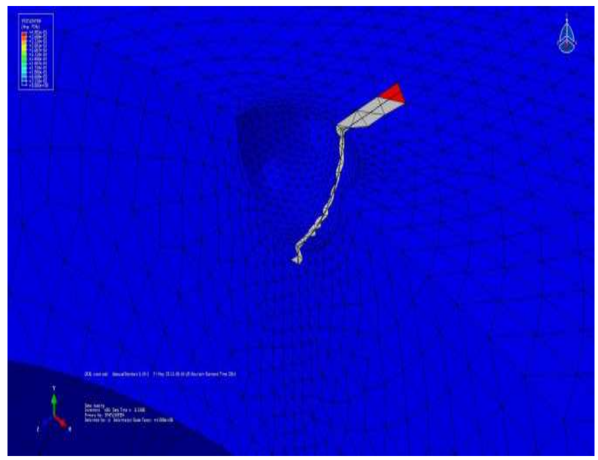
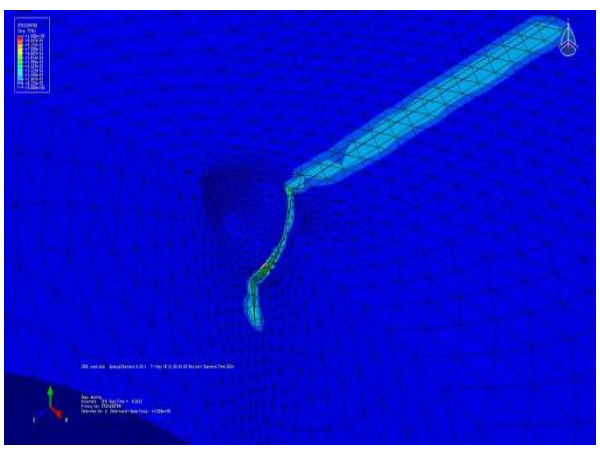
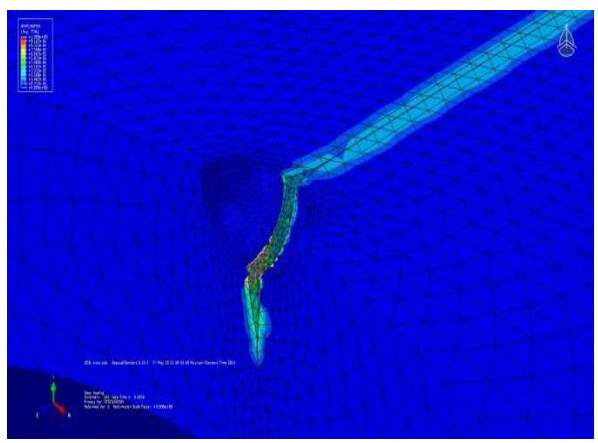
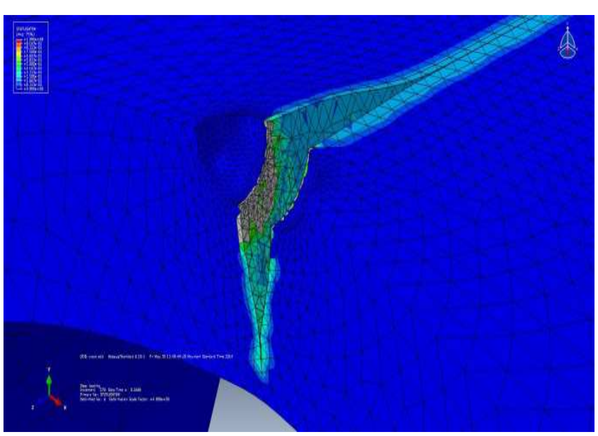
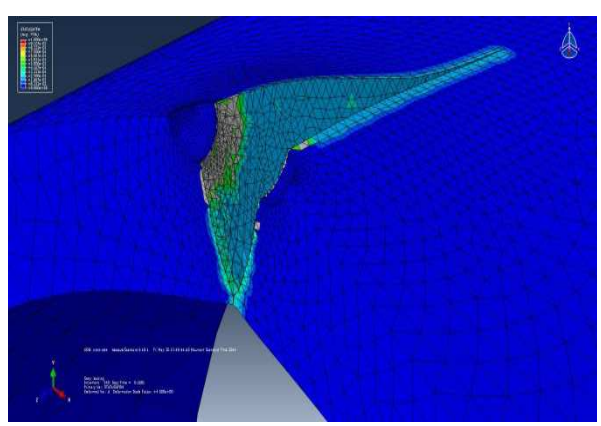

Fig. 6 Crack Propagation behavior using XFEM simulation

One parametric studies were carried out by considering cavity radius effect on the crack initiation pressure of the pipe. Cavity radius was varied keeping internal and outer diameter and loading constant. Attached below is the data compiled from the simulations. The results are also shown in Fig. 7

Sl. No.	Cavity Radius	Pi - PA11	Pi - HDPE
1	3.5	4.7016	2.9016
2	5	4.5816	2.7816
3	6.5	4.4616	2.7816
4	8	4.2216	2.6616
5	9.5	3.8616	2.4216

- Table 1: Cavity radius

It can be observed from the graphs that the increase of the cavity radius decreases the crack initation pressure. HDPE pipes are comparatively weaker as for the same loading the crack initiates at a lower pressure. It should be mentioned that the results here are only using simplified constitutive models. Detailed study with experimental validation needs further investigation.

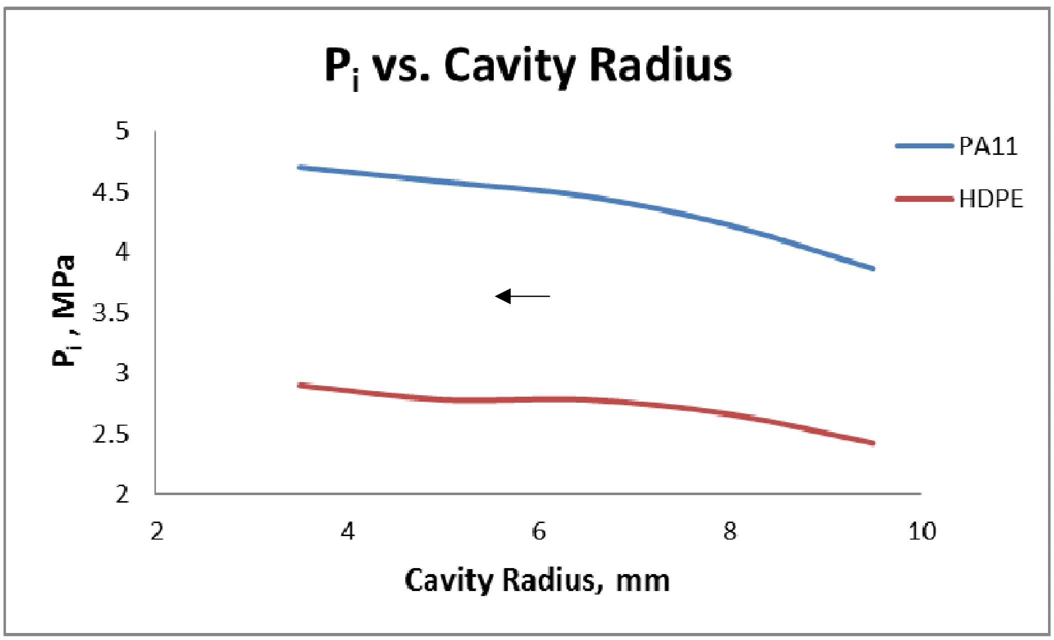

Fig. 7 P_i vs. Cavity Radius

Description of any Problems/Challenges

The project progress is satisfactory according to the schedule of tasks table. Good communications between the PIs, students and program director is well maintained. There are a few technical challenges identified and will be addressed in the future quarters, which is listed as follow:

<u>Compressed Sensing Based Fast Data acquisition</u>:
The existing data acquistion (DAQ) system using DMM approach is not efficient and the sampling rate is limited. The high speed National Instrument (NI) DAQ module (supported by the university CU PMP fund) was integrated into the current imaging DAQ module and the imaing speed has be improved by a factor of 5. One new CAAP14 master student, Mr. Deepak Kumar has been working on the Compressed Sensing (CS) based fast data acquistion and reconstruction. Thorough literature review has been conducted in Q1.

PA samples acquistion from ARKEMA:
Sample specifications were discussed among CU-Denver, ASU and Arkema, and samples preparation was ongoing. Three different samples will be provided to both universities: 1. Tensile Bars - ASTM Type 1 tensile bars will be prepared in Arkema lab in PA; 2. Plaques - 200 x 200 x 3mm plaques will be prepared in Arkema facilities in France or in PA. It was determined that CU and ASU will get them directly from PA to save time. 3. Pipes sections – Arkema's customer that buys their resin to make the pipe may have some 4 inch pipe in inventory, which needs further confirmation. It was promised that the samples will be ready in February and the PIs will work closely with industry partners. Information disclosure agreement/MOU has been signed by CU, ASU and Arkema.

(c) Planned Activities for the Next Quarter

Besides the planned activities mentioned in section (b), here are the future work for the next quarter:
Development of 3D EFG simulation model:
The current EFG codes are two-dimensional and unrealistic for the actually pipe geometry. A new CAAP PhD student has been assigned to work on the modeling part at CU, which is significantly different from the proposed modeling work for another DOT CAAP13 project. Due to the complexity of the problem, both self-developed codes and commercial software packages with careful customization will be evaluated first. The first version of the 3D EFG simulation codes is expected to be running and be valided in Q2.

Imaging system optimization: Within Q1, the CAAP team at CU further improved the imaging system resolution with the collateral support from CAAP 13. The phase information of the measured NFMW signals has been successfully extracted, however further post-processing and data fusion techniques are needed to better understand the acquired images, which are under investigation. More results are expected to be generated and reported at the end of Q2.

Presentation at the annual 24th ASNT Research Symposium: In Q2, the CAAP PhD students, Mr. Salem Egdaire and Ms. Xiaoye (Mia) Chen will attend the 24th ASNT research Symposium. Last year's presentation at the ASNT research meeting was a success and the CAAP students established a good and fruitful relationship with ASNT community. Industry mentors were identified which will help the progress of this DOT project positively. The CU-Denver received intivation to submit multiple manuscripts and presentations to this coming ASNT annual meeting. The DOT will be recognized in the presentation and award banquet for supporting this research. The CAAP students were encouraged to submit ASNT travel grants, which are upon approval at the end of Q1.

XFEM simulation with multiphsics damage coupling: Following the previous kick offmeeting and phoen discussions, it was identified that other environmental damage may contribute to the final failure of pipeline systems, such as diffusion. ASU team is working on a general methodology to include this type of damage in the current simulation framework,